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J-INTEGRAL AND HRR FIELD ASSOCIATED WITH STABLE CRACK GROWTH IN THIN ALUMINUM SEN SPECIMEN

by

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ABSTRACT

Moiré interferometry with line densities of 1200 and 40 lines per mm was used to determine the two orthogonal displacements surrounding a stably extending crack in a 2024-T3 aluminum alloy, single edge cracked specimen. The test protocol consisted of using the fine moiré grating prior to and up to a crack extension of Δa = 1.3 mm and then switching to the coarse grating for stable crack growth of Δa = 8 mm. The displacement fields were used to compute the J-integrals for various contours during crack tip blunting and crack extension. As expected, the far-field J-integral value prior to stable crack growth coincided with the LEFM strain energy release rate, *G*, and validated the experimental procedure. However, the J values obtained from the near tip contour increased slowly while the far field J values increased rapidly with increasing stable crack growth. The HRR displacement field was computed from the experimentally determined far field J. As expected the HRR displacement field agreed with the measured displacement field prior to stable crack growth since J = G_I. However, the HRR horizontal displacement field progressively deviated from the measured values with crack extension.

KEYWORDS

Elastic-plastic fracture mechanics, J-integral, HRR field, SEN fracture specimen, moiré interferometry.

INTRODUCTION

For the past five years, the authors and their colleagues have used experimentally determined displacement fields to compute directly the J-integral in thin aluminum fracture specimens (Kang and Kobayashi,1988; Dadkhah and Kobayashi, 1990, 1992, 1993; May et al, 1993). The contour integration was performed using the definition of J-integral (Rice, 1968) with the added assumption that the elastic-plastic response of the specimen material could be represented by a power hardening form with experimentally determined power hardening coefficients. These J-integral values agreed well with the corresponding elastic values under low load and with the known elastic-plastic solutions (Kumar et al, 1981) at higher loads prior to stable crack growth. Under a small stable crack growth of 1 to 3 mm, however, the J-integral values increasingly deviated from the known solutions (Kumar et al, 1981) and were as much as one quarter of that computed by the aforementioned EPRI Elastic-Plastic Handbook values.

These J-integral values were then used to compute the HRR displacement field (Hutchinson, 1968; Rice and Rosengren, 1968) and then compared with the original

measured displacement. Theoretically the HRR displacement field should have coincided with the measured displacement field within the experimental and numerical error bounds. In reality, the measured and HRR displacements perpendicular to the crack, i.e. the v-displacements, agreed well but substantial differences were formed in the corresponding values for the displacements parallel to the crack, i.e. the u-displacements. Attempts were also made to characterize the second order term in the crack tip asymptotic displacement field which is defined here as the difference between the measured and HRR displacements. While not conclusive, the results suggested that neither parameter characterization by the Q-stress (O'Dowd and Shih; 1991, 1992, 1993), nor the T-stress (Betegon and Hancock; 1991), appeared to prevail in our studies. Thus, without the presence of a HRR field or HRR field with the higher order terms at the elastic-plastic crack tip, the much heralded J-integral loses its physical significance as the strength of the HRR singular field.

Many theoretical and numerical studies related to the J-integral and the HRR field have been published since 1968. Much of these studies were limited to computing the J-integral values for various plane strain, boundary value problems and the extent of the J-dominant region which is synonymous with the HRR field. Also higher order terms for the asymptotic stress, strain and in some cases the deformation fields for a plane crack tip field in a power hardening material were derived by Li and Wang (1986), Sharma, S.M. and Aravas, N. (1991), Yang et al (1993) and Xia et al (1993). Noteworthy in these theoretical analysis is the two-parameter, ductile fracture criterion, which was suggested by Li and Wang (1986), based on a critical J_{IC} and the high triaxial stress ahead of a plane strain crack front. This two-parameter ductile fracture criterion was the subject of extensive finite element analysis by Shih and his associates. In particular, the Q parameter, which is the triaxiality parameter as defined by O'Dowd and Shih (1991, 1992), together with the J-integral formed the basis of the J-Q theory of fracture. More recently, Wang and Shih (1993) has shown that the cumulative sum of the higher order terms is equivalent to the triaxial stress and thus O'Dowd and Shih (1993) has redefined Q to represent the entire difference between the actual crack tip stress and the HRR singular component. For small scale yielding, the triaxiality parameter, Q, was related to the elastic T-stress and that the J_{IC} versus Q relation predicted from the J-Q ductile fracture criterion correctly predicted the experimental results by Kirk et al (1993).

Most of the literature discussed above were related to the state of plane strain of a stationary crack tip. The experimental investigation, which was described previously, involved a near plane stress state with inevitable stable crack growth. This state of plane stress effectively eliminates the triaxiality constraint, which is the basis of the J-Q theory, and thus the J-Q theory is not applicable for evaluating the test results of thin fracture specimens.

Limited theoretical analysis of the higher order asymptotic crack tip field in plane stress has been conducted by Yang et al (1993a, 1993b). For a power hardening coefficient of $n = 3$, their three term displacement solution effectively predicted the u-displacement while the v-displacement required only the HRR singular component. These results are in qualitative agreement with the results of the authors and their colleagues with the exception that the HRR displacement under predicted the measured u-displacement. In a recent note, Chao (1993) has indicated that for a mode I plane stress state with $n > 3.2$, the higher order terms are uniquely governed by the J-integral and thus ductile fracture for such case can be characterized by a single parameter of J. This important conclusion is in qualitative agreement with the results of Dadkhah and Kobayashi (1993) who showed that throughout a stable crack growth of $\Delta a = 2.5$ mm, the v-displacements, which was uniquely represented by the J-integral values, were nearly

identical in 2024-0 aluminum alloy, single edge notched (SEN) specimens and biaxially and uniaxially loaded cruciform specimens.

The above brief review indicates that further theoretical and experimental analyses is needed before the two parameter fracture criterion such as the J-Q or J-T theory can be applied to a plane stress fracture specimen. The purpose of this paper is provide additional such experimental evidence.

TWO-PARAMETER CRACK TIP STATE

The high order asymptotic elastic-plastic crack tip stress field by Li and Wang (1968), Sharma and Aravas (1991) and Yang et al. (1993) is based on the J_2 deformation theory with the following power hardening material of Ramberg-Osgood:

$$\varepsilon_{ij} = \frac{1+\nu}{E} s_{ij} + \frac{1-2\nu}{3E} \sigma_{kk}\delta_{ij} + \frac{3}{2} \alpha\varepsilon_o \left(\frac{\sigma_e}{\sigma_o}\right)^{n-1} \frac{s_{ij}}{\sigma_o} \tag{1}$$

where i, j = 1 or 2 corresponds to a Cartesian coordinate system with axes parallel or perpendicular to the crack, respectively, E and ν are the modulus of elasticity and Poisson's ratio respectively, σ_o and ε_o are the yield stress and strain, respectively, α and n are material constants, σ_e, and s_{ij} is the equivalent and deviatoric stress, respectively.

For a plane stress state, Gang et al (1994) has shown that the two term representation of the asymptotic crack tip field, in polar coordinates, can be represented at the crack tip as

$$\begin{aligned}
u_i(r,\theta) &= \alpha\varepsilon_o r \left(\frac{J}{\alpha\varepsilon_o\sigma_o I_n r}\right)^{\frac{n}{n+1}} u_{i1}(\theta,n) + \varepsilon_o r \left(\frac{J}{\alpha\varepsilon_o\sigma_o I_n r}\right)^{\frac{1}{n+1}} u_{i2}(\theta,n) \\
\varepsilon_{ij}(r,\theta) &= \alpha\varepsilon_o \left(\frac{J}{\alpha\varepsilon_o\sigma_o I_n r}\right)^{\frac{n}{n+1}} \varepsilon_{ij1}(\theta,n) + \varepsilon_o \left(\frac{J}{\alpha\varepsilon_o\sigma_o I_n r}\right)^{\frac{1}{n+1}} \varepsilon_{ij2}(\theta,n) \\
\sigma_{ij}(r,\theta) &= \alpha \left(\frac{J}{\alpha\varepsilon_o\sigma_o I_n r}\right)^{\frac{n}{n+1}} \sigma_{ij1}(\theta,n) + \frac{\sigma_o}{\alpha} \left(\frac{J}{\alpha\varepsilon_o\sigma_o I_n r}\right)^{\frac{2-n}{n+1}} \sigma_{ij2}(\theta,n)
\end{aligned} \tag{2}$$

where

$$J = \int_\Gamma [W\, dx_2 - \sigma_{ij} n_j u_{i,x1} ds] \tag{3}$$

and

$$W = \int_\varepsilon \sigma_{ij} d\varepsilon_{ij} \tag{4}$$

i,j = 1,2 corresponds to a cartesian coordinate system with its origin at the crack tip, n_j represents a unit vector normal to any contour which encloses the crack tip, $u_{i2}(\theta,n)$,

$\varepsilon_{ij}(\theta, n)$, and $\sigma_{ij}(\theta, n)$ are tabulated angular functions (Yang et al, 1993; Shih, 1983) of the polar coordinate, θ, and hardening exponent, n, and I_n is a tabulated constant (Shih 1983).

Equations (1), (3) and (4) can be used to evaluate directly the J-integral from the measured displacement field along rectangular contours which encompass the crack tip. First the strain field at each loading stage is computed from the measured displacement field at a given point on the contour. Then the corresponding stress is computed from equation (1) and together with the measured strain, the strain energy density is determined. Details of this analysis based on the deformation theory of plasticity, which was also the basis of original definition of J (Rice, 1968), and the numerical integration procedure is given in Kang and Kobayashi (1988).

The J-integral value determined above was then substituted in to equation (2) to compute the HRR singular displacement terms. The second order term could not be computed since the corresponding u_{i2} was not given in Yang et al (1993a). Assuming that the second order term is much larger than the sum of the remaining higher order terms, an indirect check on the second order term can be made by noting that it varies as $r^{n/(n+1)}$.

EXPERIMENTAL ANALYSIS

Experimental Procedure

The orthogonal displacement components surrounding the crack tip were measured by moiré interferometry using two specimens, each with a different grating. The first specimen was coated with a fine, cross diffraction grating of 1200 lines/mm and was used in the initial phase of loading. prior to stable crack growth. The second specimen was coated with a relatively coarse, cross diffraction grating of 40 lines/mm and was used to record the crack displacement after stable crack growth commenced. This coarse grating was necessary due to the gross yielding and the large strain components, which will generate a moiré fringe pattern too dense to resolve, associated with the large stable crack growth in a ductile specimen. The fine, cross diffraction grating was transferred using the procedure of Post (1987). The coarse, crossed diffraction grating was transferred onto the specimen surface using photoresist and is similar to the procedure developed by Ifju and Post (1991). However, in this study, the highly polished surface of the aluminum specimen provided sufficient reflectivity and thus an evaporated aluminized coating was not used. This reflective specimen surface also eliminated the loss of moiré fringes at high strain where an aluminized coating may craze and obliterate the diffraction grating.

The specimen was illuminated by a four beam moiré interferometer (Guo and Kobayashi, 1993) for simultaneous recording of the two orthogonal displacement fields. Figure 1 shows the moiré interferometry setup and the u-v mirror arrangement used in this study. The coarse diffraction grating reduced the incident angle of the four beams thus simplifying the u-v mirror supports.

Specimen

The specimen consisted of a fatigue precracked, thin single-edged notch (SEN), 2024-T3 aluminum alloy specimen shown in Figure 2. The moiré diffraction grating covered a region of 25.4 x 50.8 mm surrounding the crack as shown. Also shown schematically are the integration contours. The SEN specimen was subjected to uniaxial tensile loading in a displacement controlled testing machine and the moiré interferometry patterns were recorded at various stages of stable crack growth.

NUMERICAL ANALYSIS

A commercial finite element code was used to compute the elastic-plastic state associated with stable crack growth in this specimen. The objective of this numerical analysis was to generate numerical results, which can be compared with the experimental results, at various stages of stable crack growth with large scale yielding. In practice however, the available code could only handle modest plastic straining associated with a small stable crack growth of Δa = 1.5 mm before collapsing.

Unlike traditional finite element (FE) analysis, the measured displacements near the boundary of the moiré grating were used as input boundary conditions to the FE model of the SEN specimen. As discussed by Hareesh and Chiang (1989) and Sivaneri et al. (1991), this procedure not only resulted in saved computer time but provided detailed information, which is lacking in the moiré analysis particularly at the initial stage of stable crack growth, in the immediate vicinity of the crack tip. Also, as described in Hareesh and Chiang (1989), this load path dependent, elastic-plastic finite element analysis must start from the early stage of plastic yielding and proceed incrementally along the loading path.

Figure 3 shows the finite element model used in this analysis. The power hardening stress-strain relation used in this incremental elastic-plastic analysis was that of Dadkhah and Kobayashi (1990). Due to the sensitivity of the FEM to displacement-prescribed boundary conditions, a second order curve, which was fitted to the measured boundary displacements obtained from moiré interferometry, was used as the input boundary condition.

RESULTS

Eleven increments of load, five and six to the specimens with the fine and coarse moiré gratings, respectively, were applied and the corresponding moiré interferometry fringes were recorded. Figure 4 shows the measured load versus the computed load line displacement for the two specimens with the fine and coarse grating. The continuity in the two relations justify the use of the two specimens in this study. The J values were then computed along three contours of 10mm x 10mm, 15mm x 15mm and 17.5mm x 25mm for each increment of loading.

Figures 5a and 5b show typical moiré fringe patterns corresponding to the displacement parallel, u, and perpendicular, v, to the crack using the fine and coarse diffraction gratings, respectively. Also shown in Figs. 5a and 5b are the rectangular contours used for the j-integral computation. This computation for the specimen with a coarse diffraction grating, using moiré interferometry data, was conducted only for the latter stages of loading with more dense moiré fringe patterns.

Figures 6a, 6b and 6c show a comparison of the various J values of interest. J_{FEM} designates the value of the J-integral computed by the commercial FE code, using the moiré fringe data as input boundary conditions, prior to and with crack extension. In this study, the J_{FEM} computation had to be terminated at Δa = 1.5 mm due to the gross distortion of the small finite elements surrounding the crack tip. J_{LEFM} was computed by J=G (strain energy release rate) based on the K_I from the stress intensity factor listing in Tada et al. (1993). J_{SHIH} was obtained using the procedure and tables of Kumar et al. (1981). J values were also obtained using an algorithm which calculated the value of the

J-integral along a designated integration contour on the moiré fringe pattern. $J_{EXPERIMENTAL}$ is the value of J associated with the largest contour. Figure 6a shows that $J_{EXPERIMENTAL}$ is in good agreement with J_{LEFM} at lower loading as expected and increasingly differs at a higher loading prior to stable crack growth. Figure 6b shows that the value of $J_{EXPERIMENTAL}$ is close to the value of J_{SHIH} at higher loads and during stable crack growth. Another point of interest is that J_{FEM} becomes highly contour dependent before a crack extension of Δa = 1.5mm is reached as shown in Fig. 6c. This is unexpected in light of previous numerical studies by Shih et al. (1981).

Figures 7a and 7b show the log-log plots of crack tip u- and v-displacements, respectively prior to stable crack growth for three angular orientations. While the measured and LEFM u- and v-displacements are in reasonable agreement, as expected at this low load, a similar agreement is not observed in the very vicinity of the crack tip.

Due to the uncertainty in the rigid body displacement component in the measured u-displacement, only the slope and not the absolute value of this displacement can be compared with the slope of the LEFM component, i.e. 0.5, and with the slope of the HRR component, which is 0.083.

Figures 8a and 8b show the log-log plots of the crack tip u- and v-displacements, respectively, at the onset of stable crack growth. The u-displacement continues to maintain its elastic response while the v-displacement is approaching the HRR displacement at about r = 1 mm.

Figures 9a and 9b, as well as 10a and 10b, show the log-log plots of the crack tip displacements for a moderate stable crack growth, i.e. Δa = 1.5 mm and 3.9 mm, respectively. The slope and the value of the v-displacement is now in good agreement with those of the HRR displacement. The slope and the value of u-displacement, however, continues to follow those and the value of the LEFM displacement.

The Q value in these figures represents the absolute value of the difference between the measured and the HRR displacement computed from the measured J values and is not the Q value used by Shih et al. The plane strain based simplified J-Q theory predict for a state of *plane stress* , vanishing Q components as per Aravas (1993). The slopes of the Q components for the u- and the v-displacements vary from 0 to 0.18 within the region of $r\sigma_0/J < 3$. In the region of $3 < r\sigma_0/J < 10$, the average slope of the Q components for the u- and v-displacements are approximately 0.9 and 0, respectively. While these values are not exactly the $n/(n+1) = 0.92$ predicted by Gang et al (1994),a qualitative agreement is noted.

CONCLUSIONS

Limited experimental results involving the crack tip displacement fields in thin aluminum SEN with small stable crack growth showed that the J-Q theory, based on the plane strain form of O'Dowd and Shih (1993), may not be present. On the other hand, the crack tip field of Yang et al. (1993) could exist.

For an elastic-plastic fracture analysis of thin plates in the presence of stable crack growth, the present J-integral computation procedures base Kumar et al. (1981) and on a commercial code must be reinvestigated in view of the observed large discrepancies.

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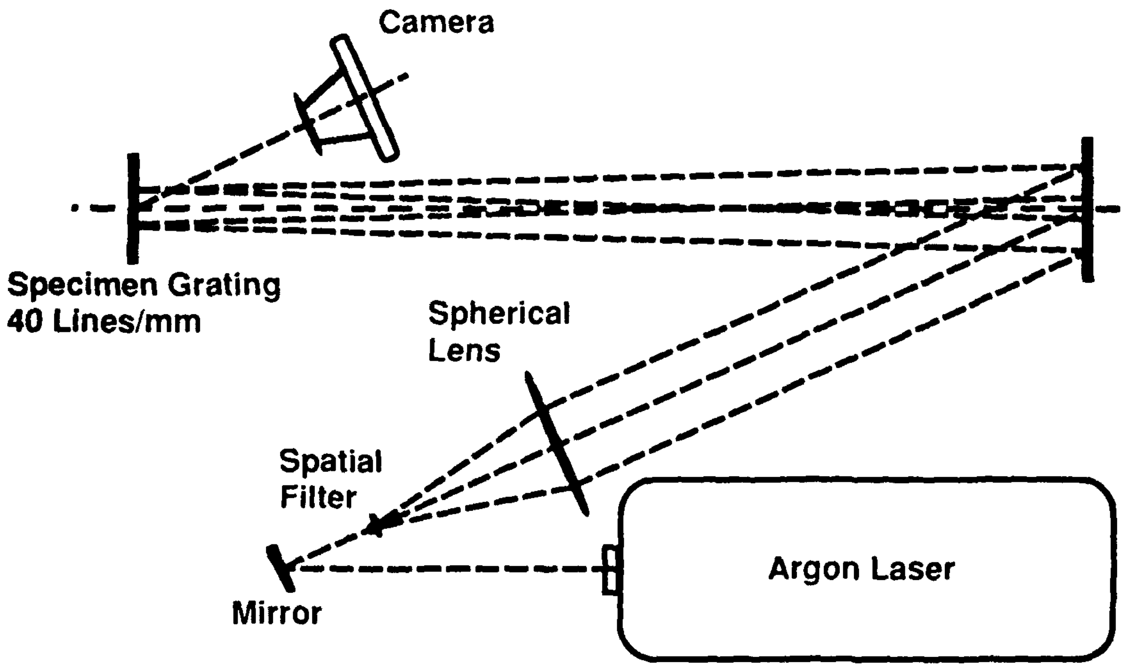
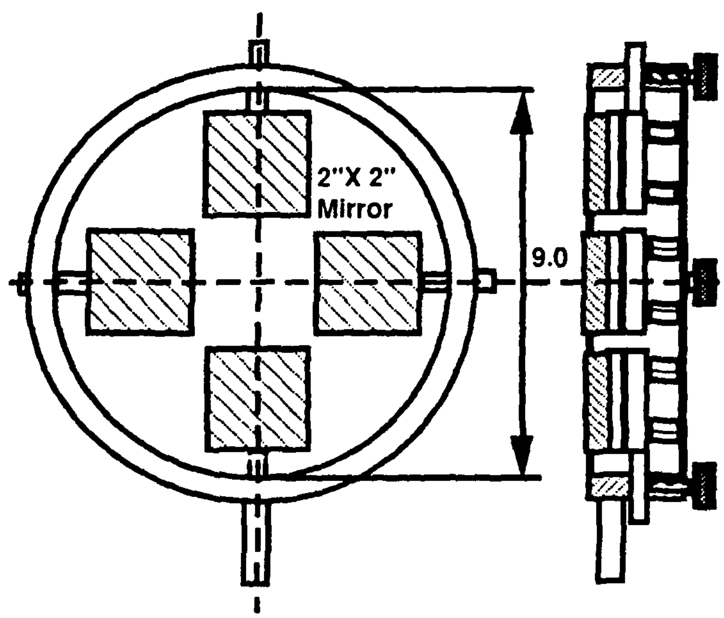


(a) Optical set--up



(b) Small u-v set-up

Figure 1. Moiré interferometry set-up

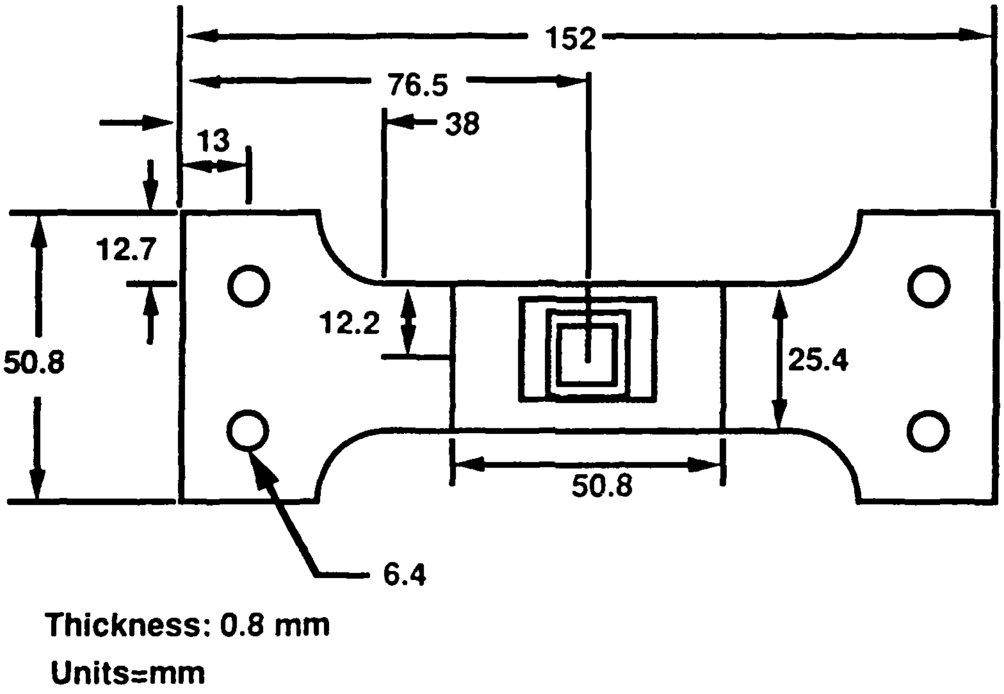


Figure 2. 2024-T3 aluminum alloy SEN specimen with J-integral contours shown

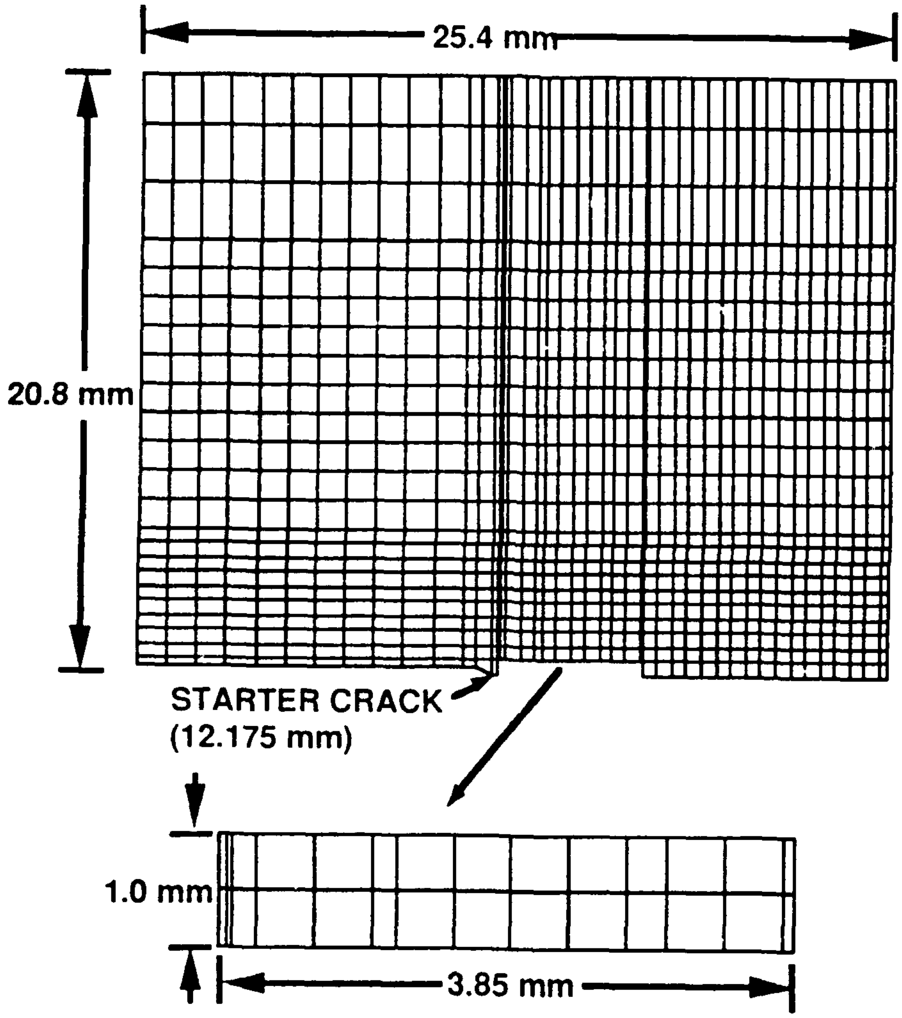


Figure 3. Finite element mesh used in elastic-plastic analysis

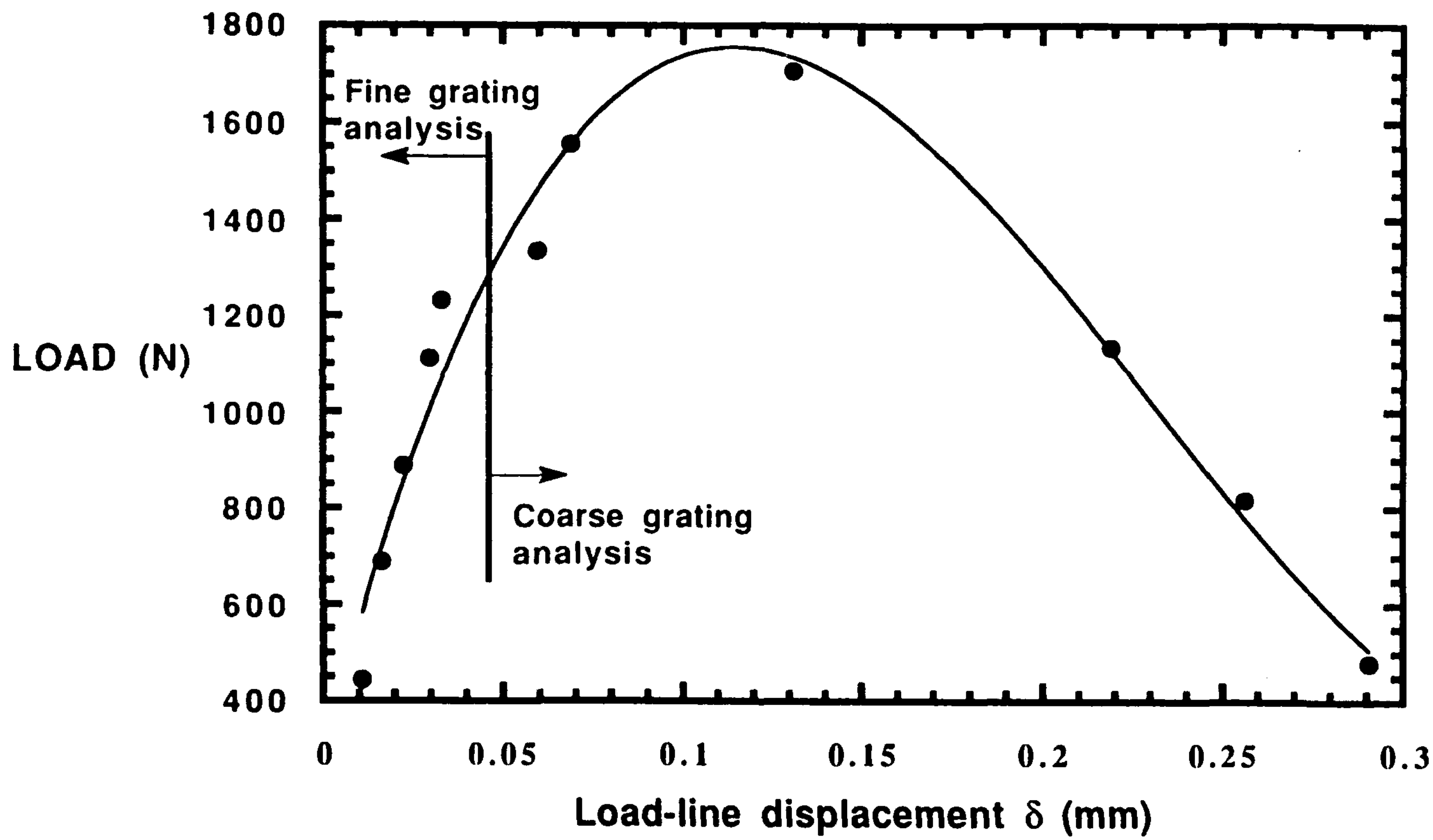
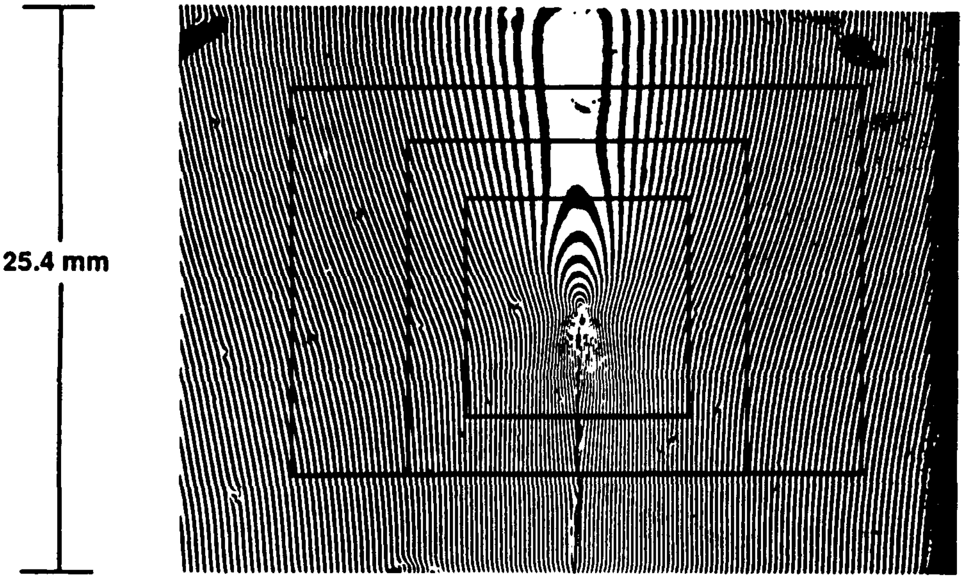
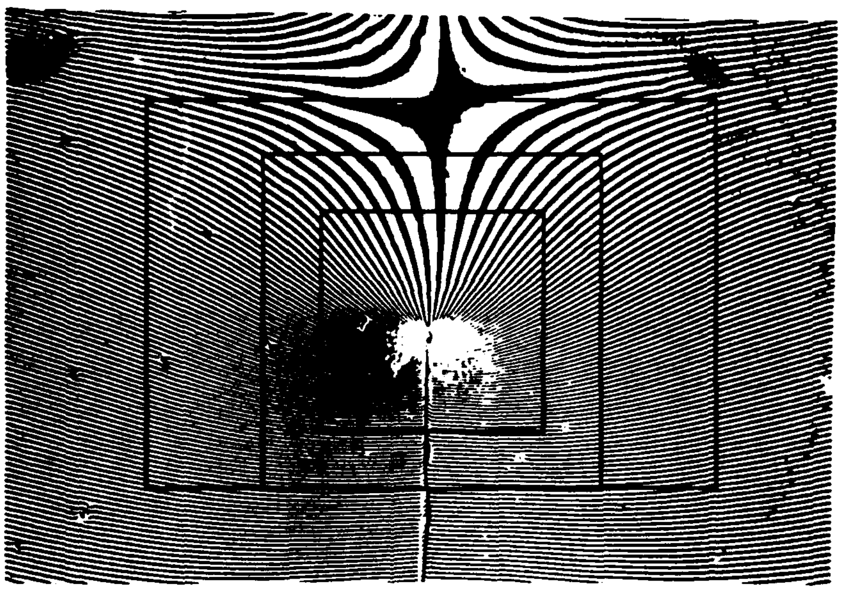


Figure 4. Load history of two 2024-T3 SEN specimens

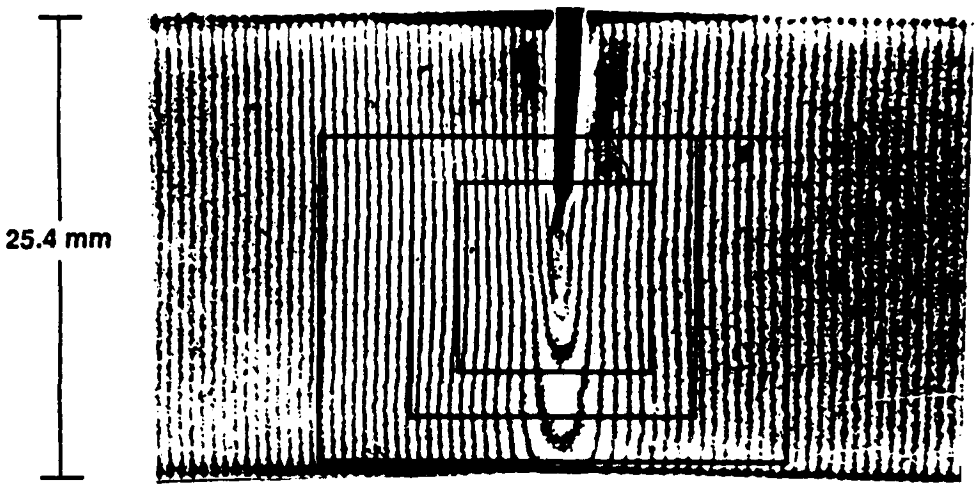


u-displacement field

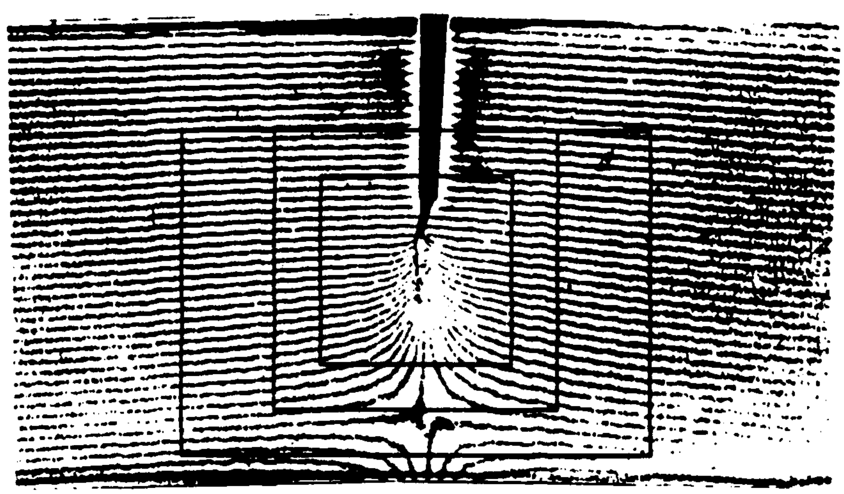


v-displacement field

Figure 5a. Moire interferometry patterns of the 2024-T3 SEN specimen with J contours shown [Load = 689.5 (N)]. Fine grid analysis



u-displacement field



v-displacement field

Figure 5b. Moire interferometry patterns of the 2024-T3 SEN specimen with J contours shown [Load = 1134 (N)]. Coarse grid analysis

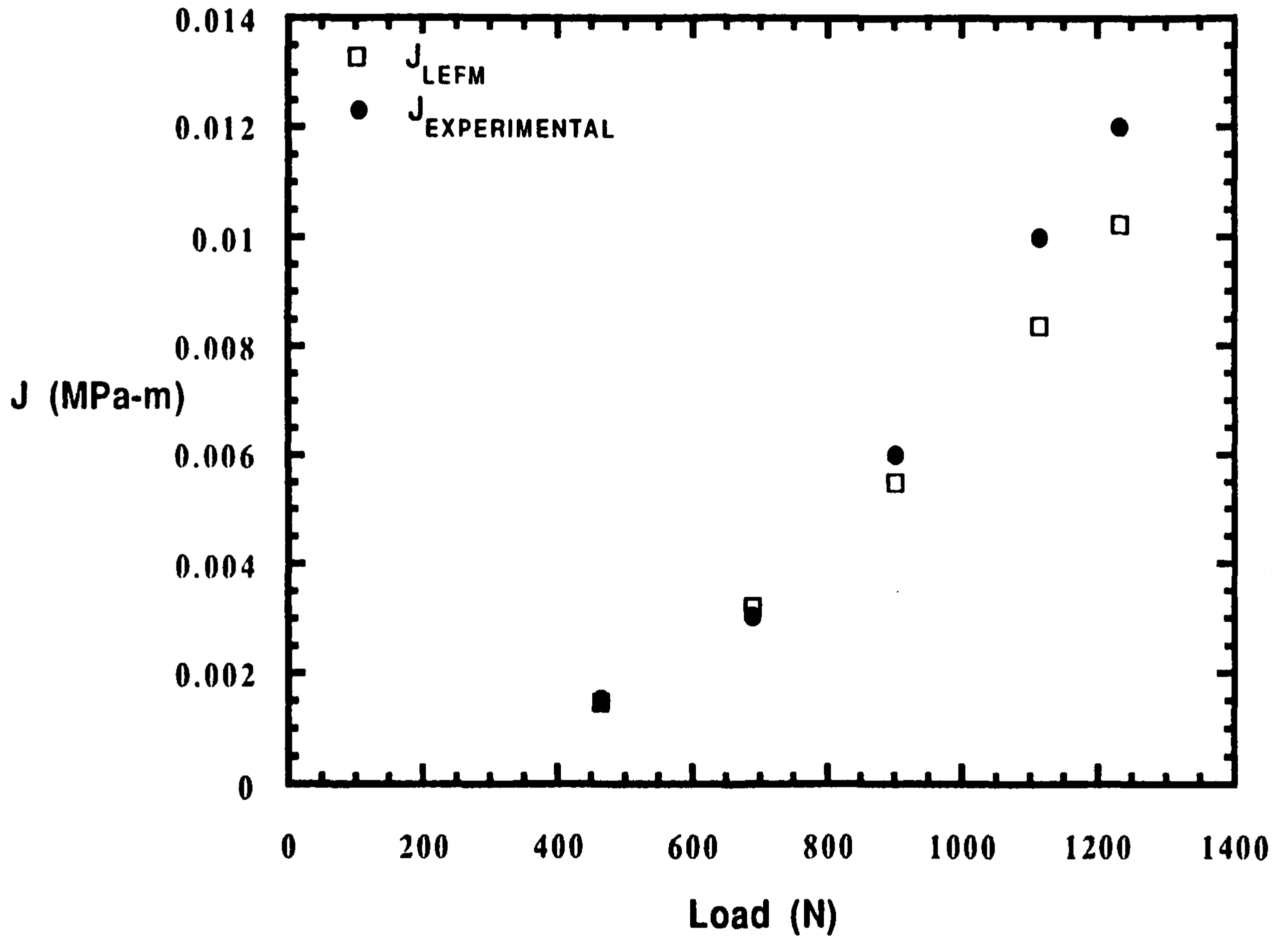


Figure 6a. J-integral values of 2024-T3 SEN specimens prior to stable crack growth

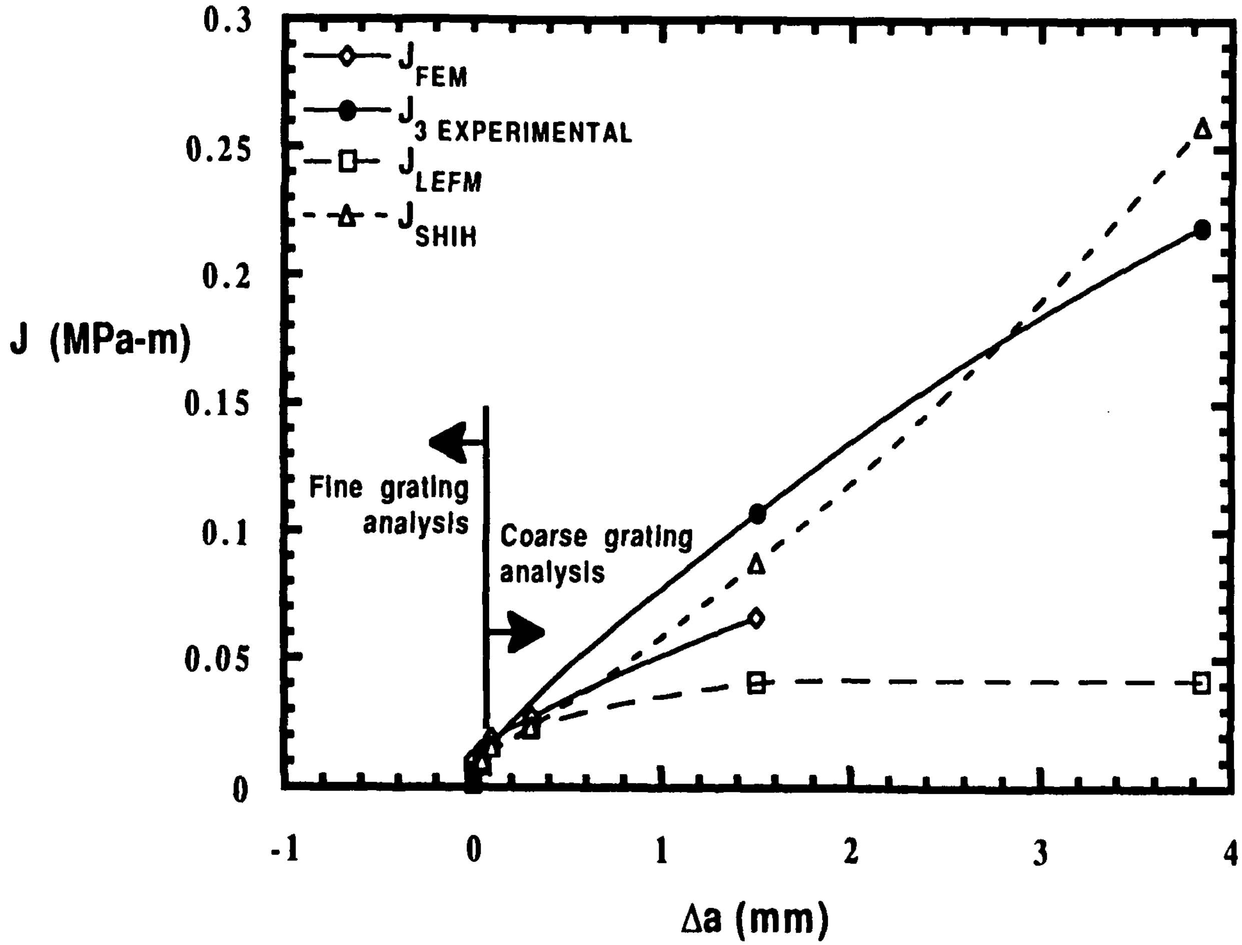


Figure 6b. J-integral values of 2024-T3 specimen under stable crack growth

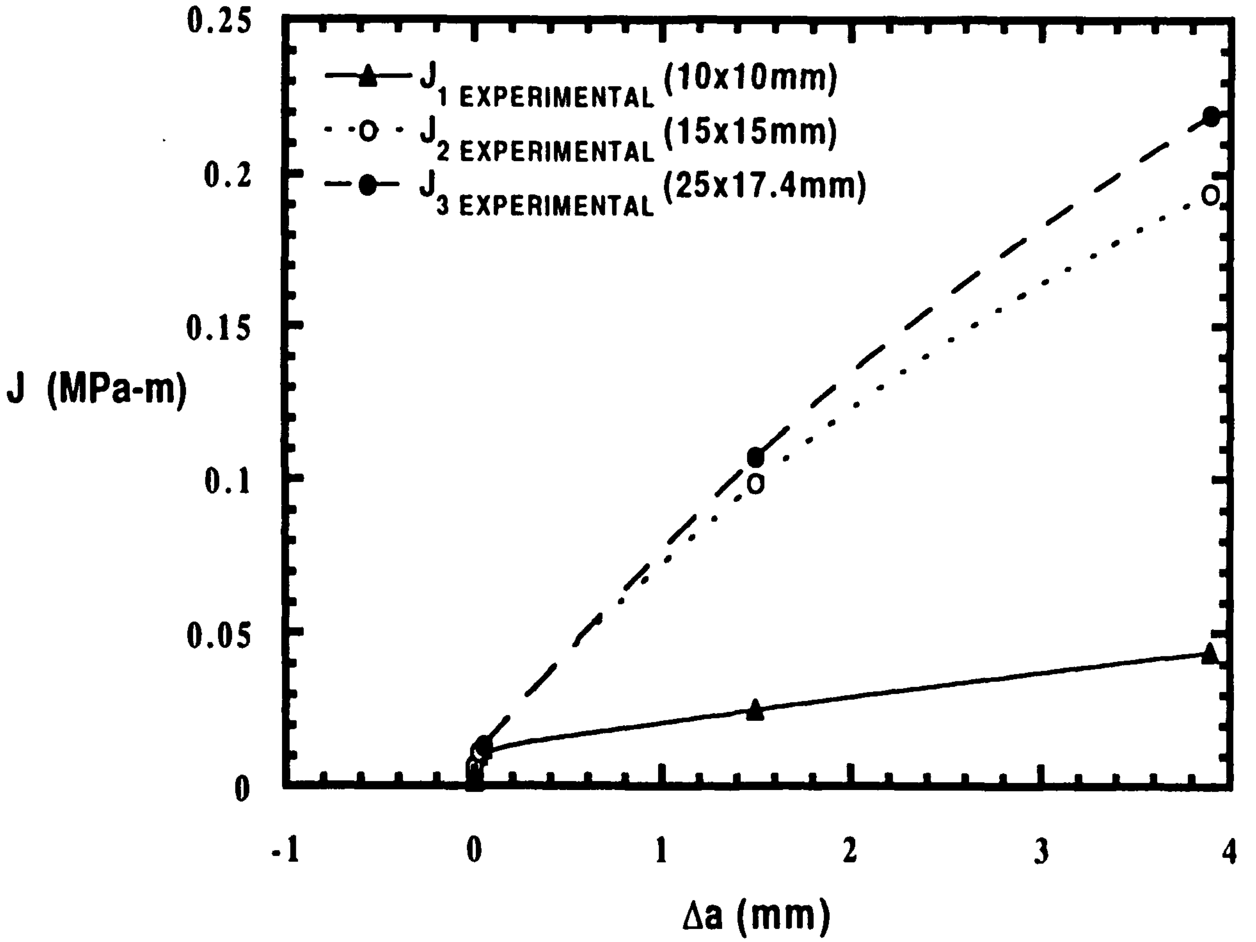


Figure 6c. Variation in the J-integral values of 2024-T3 specimen under stable crack growth

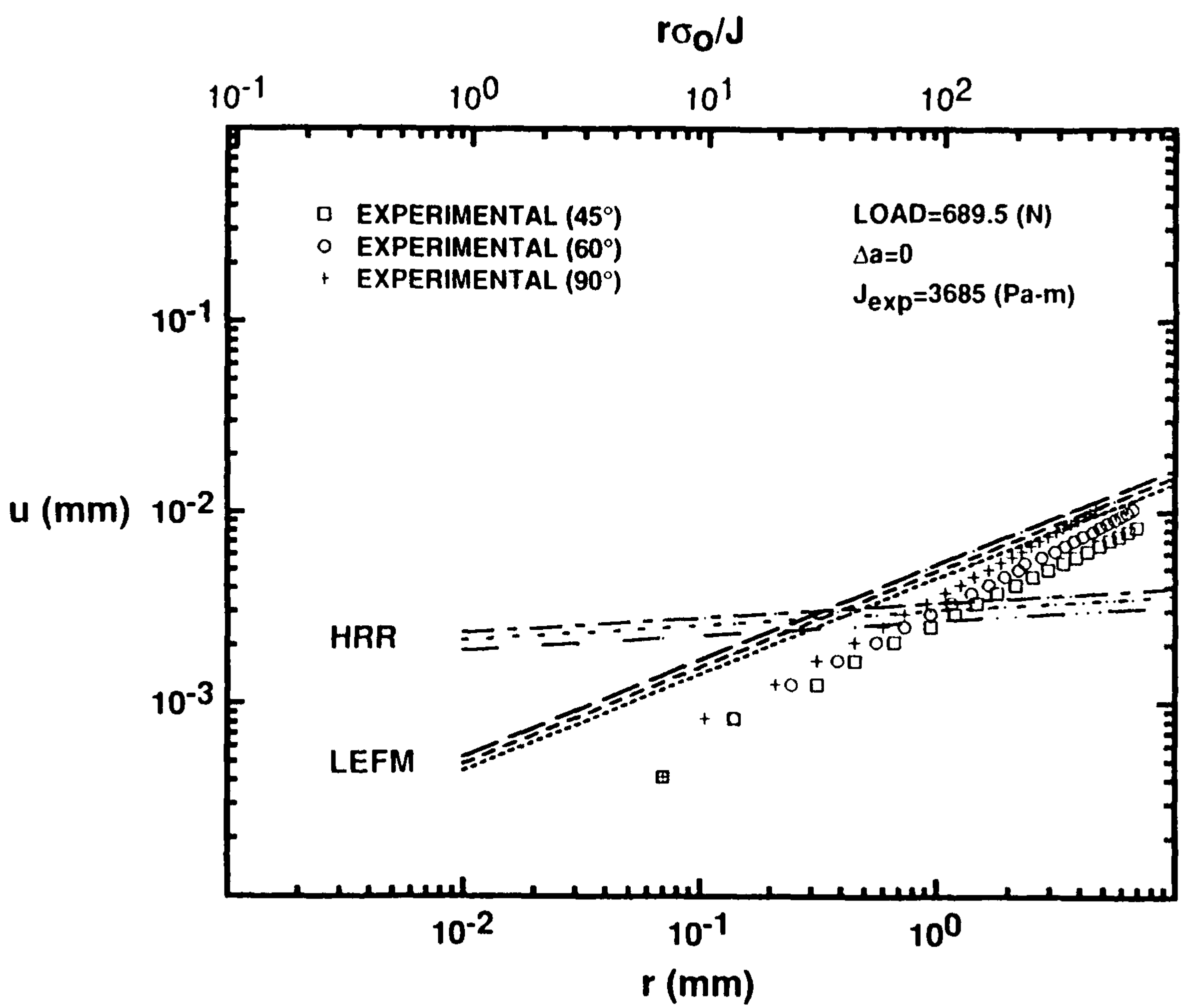


Figure 7a. Crack tip u-displacement of 2024-T3 SEN specimen prior to stable crack growth. Fine grid analysis

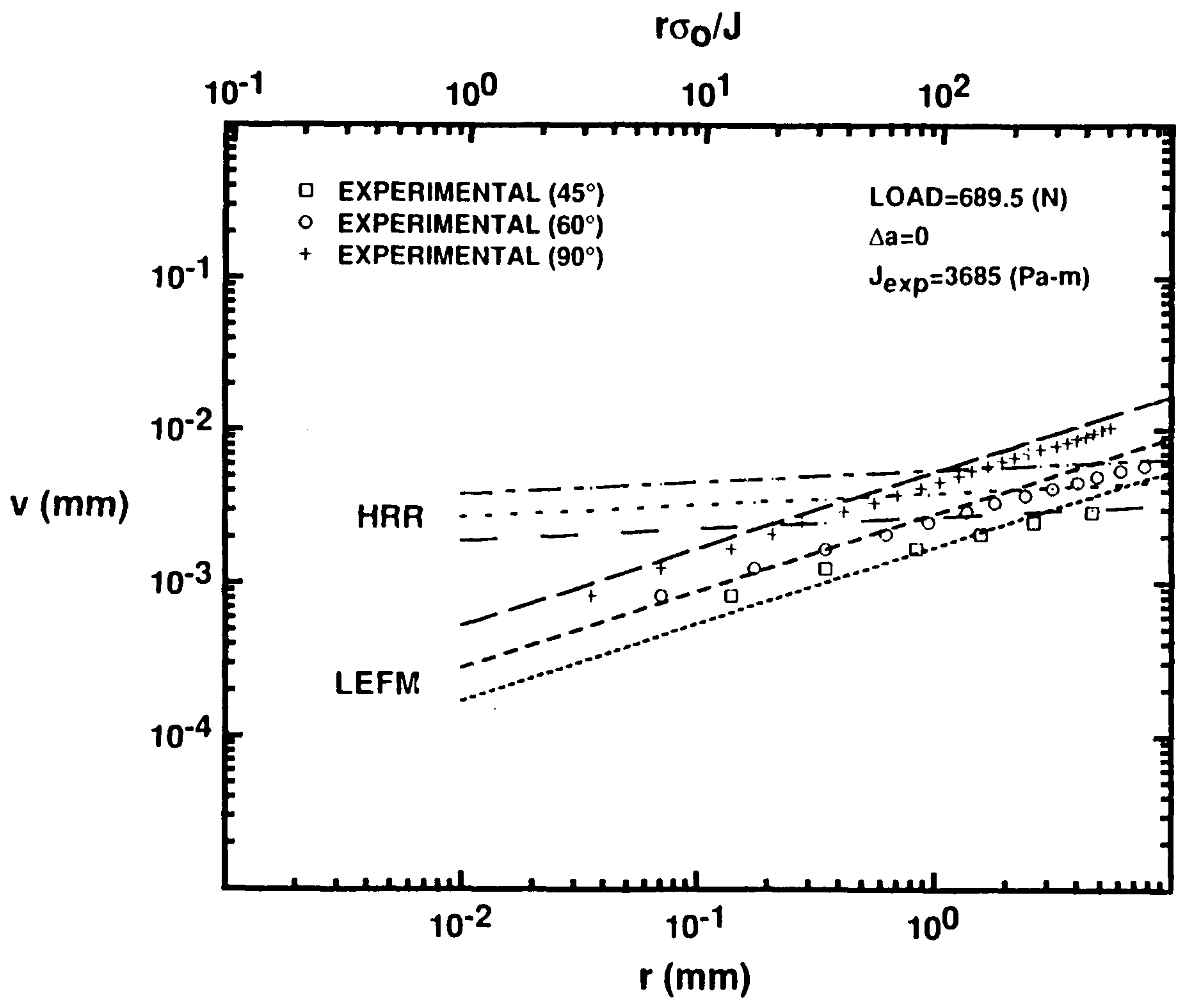


Figure 7b. Crack tip v-displacement of 2024-T3 SEN specimen prior to stable crack growth. Fine grid analysis

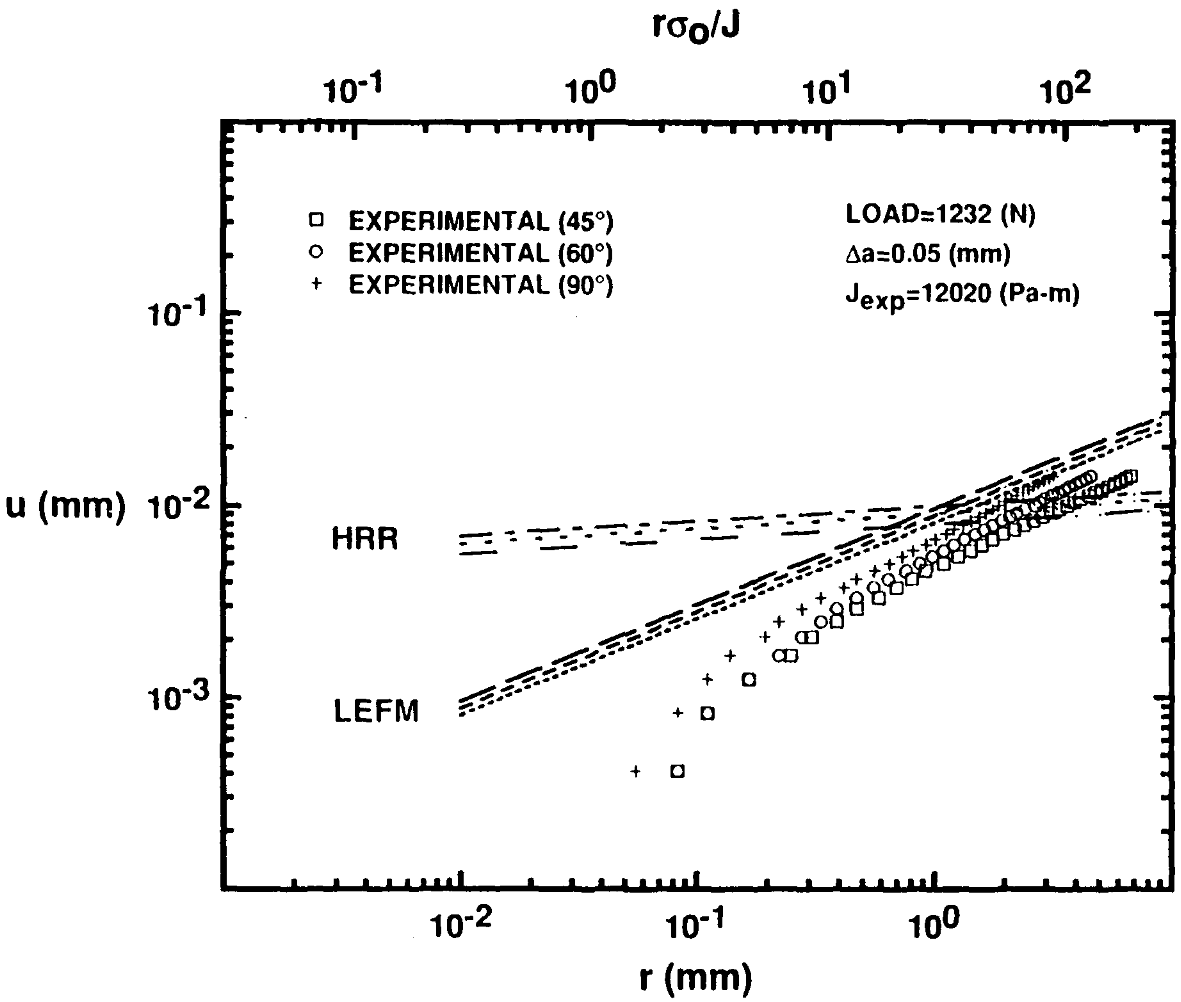


Figure 8a. *Crack tip u-displacement* in 2024-T3 SEN specimen at the onset of stable crack growth.
Fine grid analysis

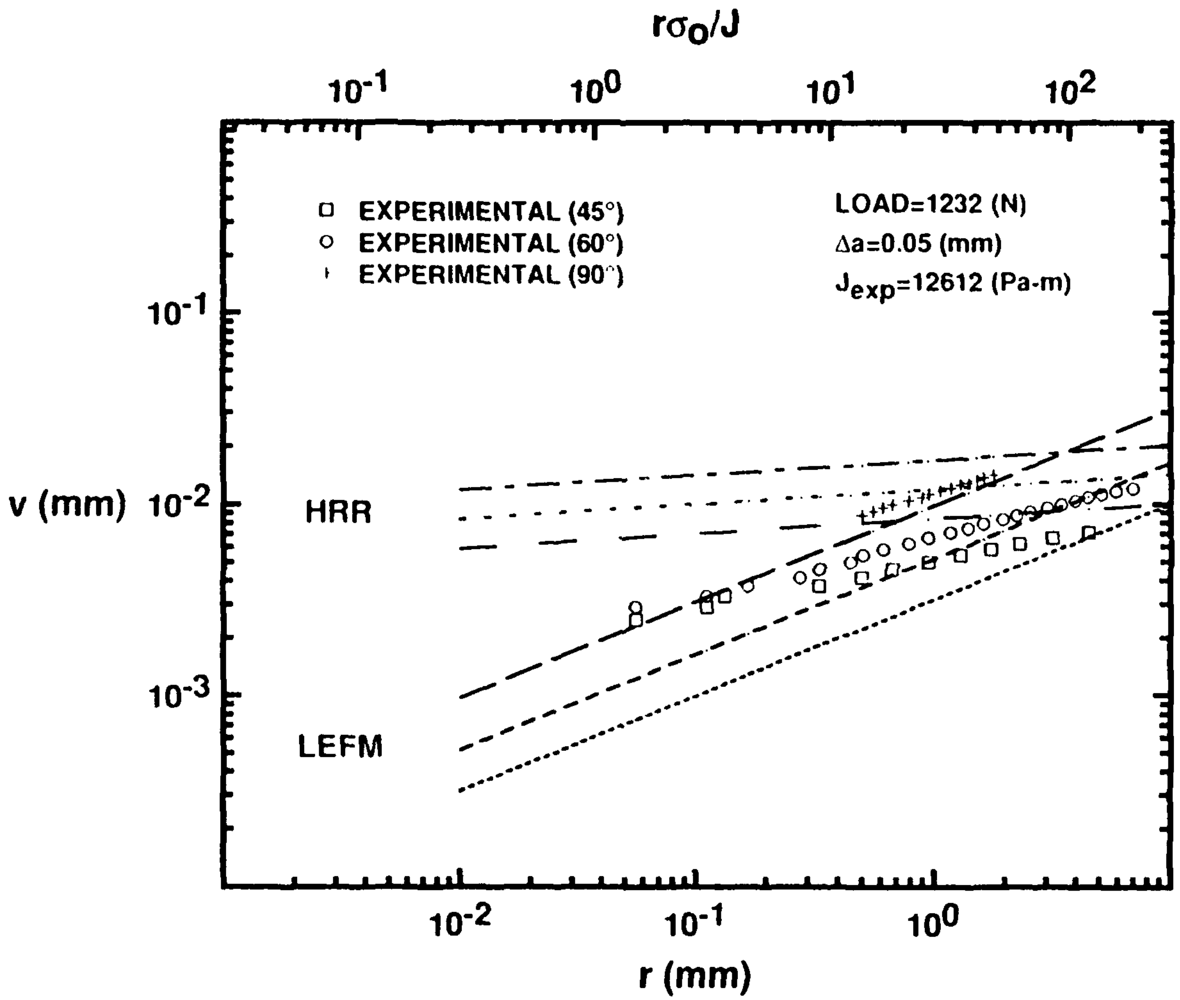


Figure 8b. Crack tip v-displacement in 2024-T3 SEN specimen at the onset of stable crack growth. Fine grid analysis

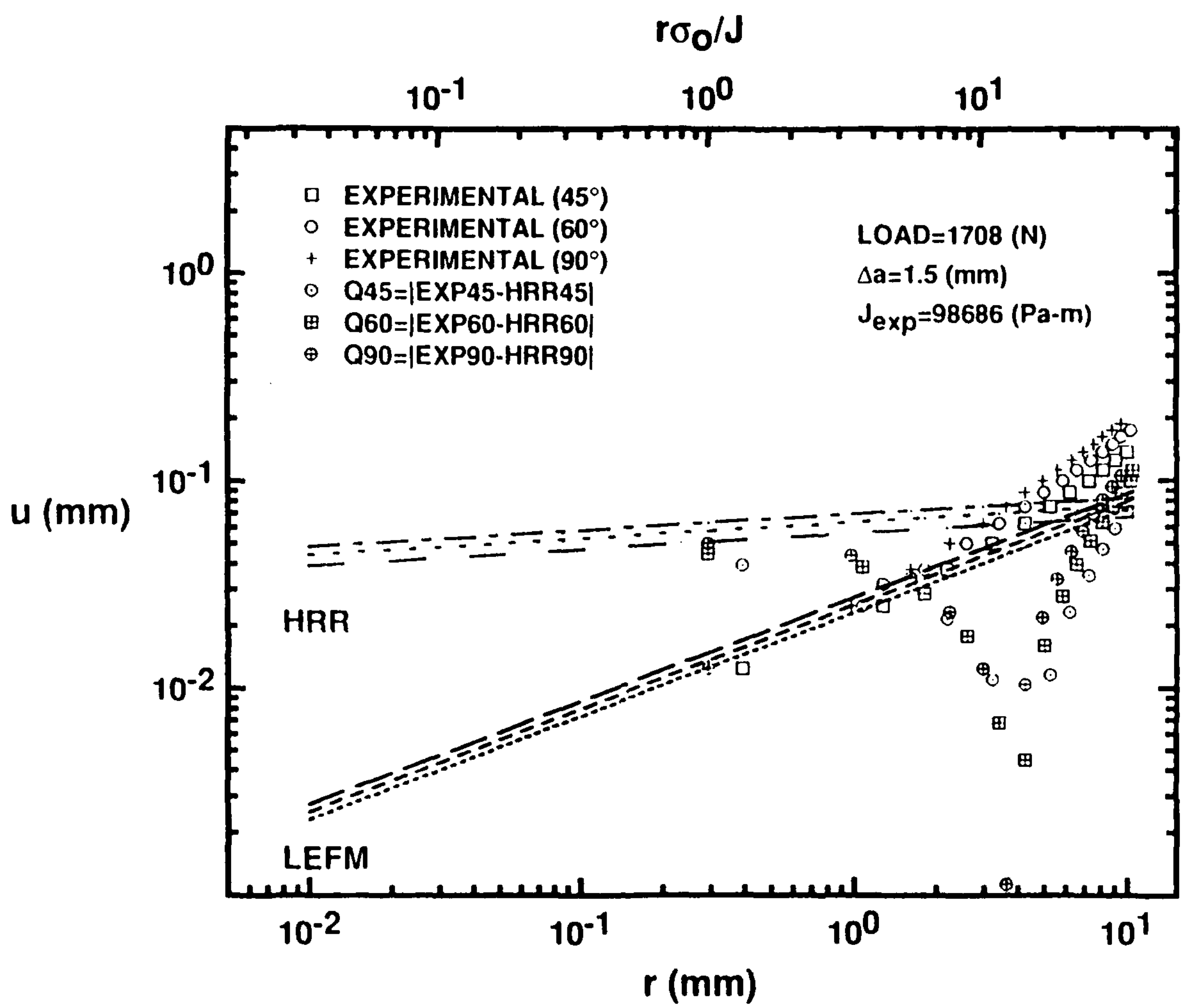


Figure 9a. Crack tip u-displacement in 2024-T3 SEN specimen with moderate crack growth. Coarse grid analysis

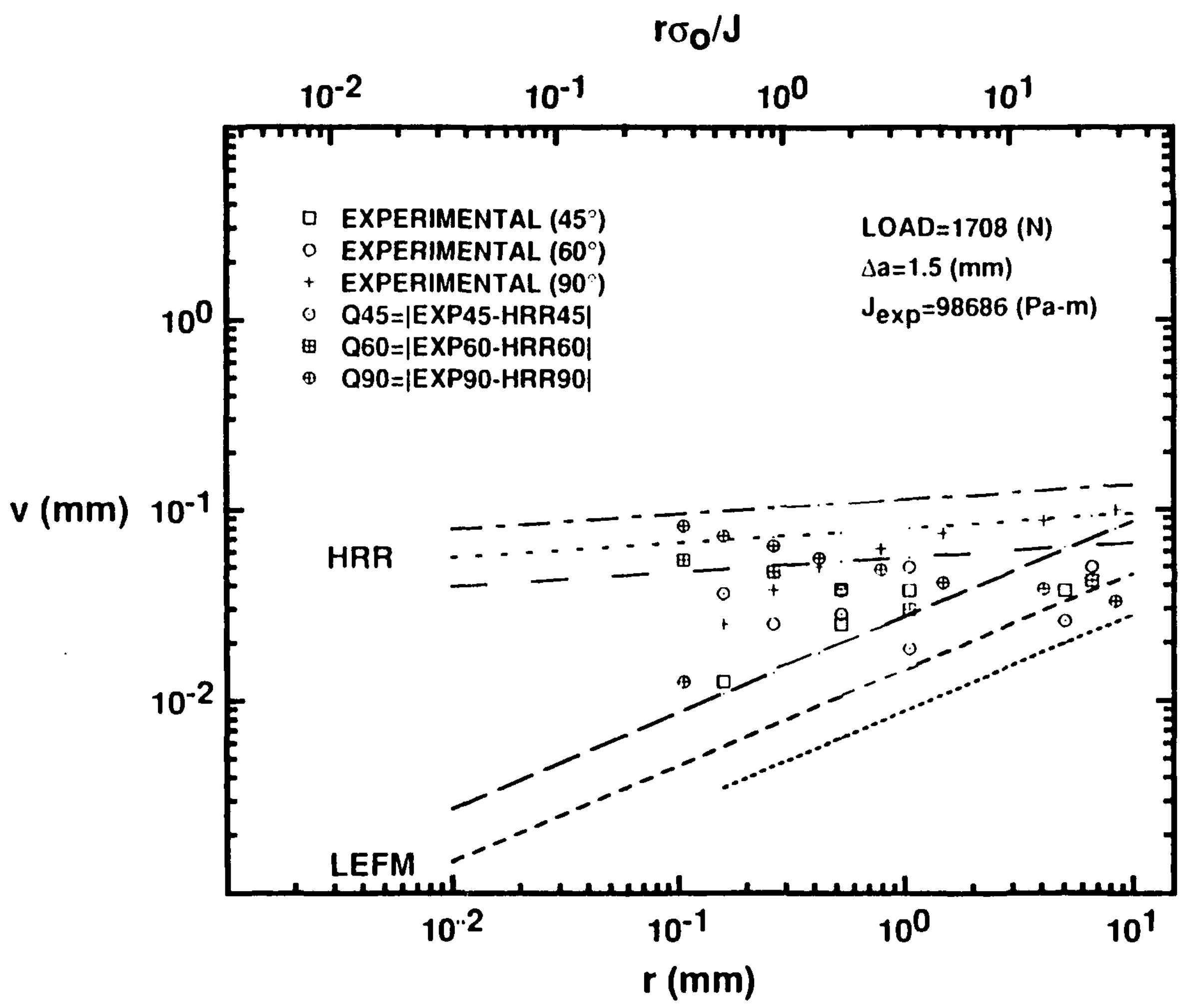


Figure 9b. Crack tip v-displacement in 2024-T3 SEN specimen with moderate crack growth. Coarse grid analysis

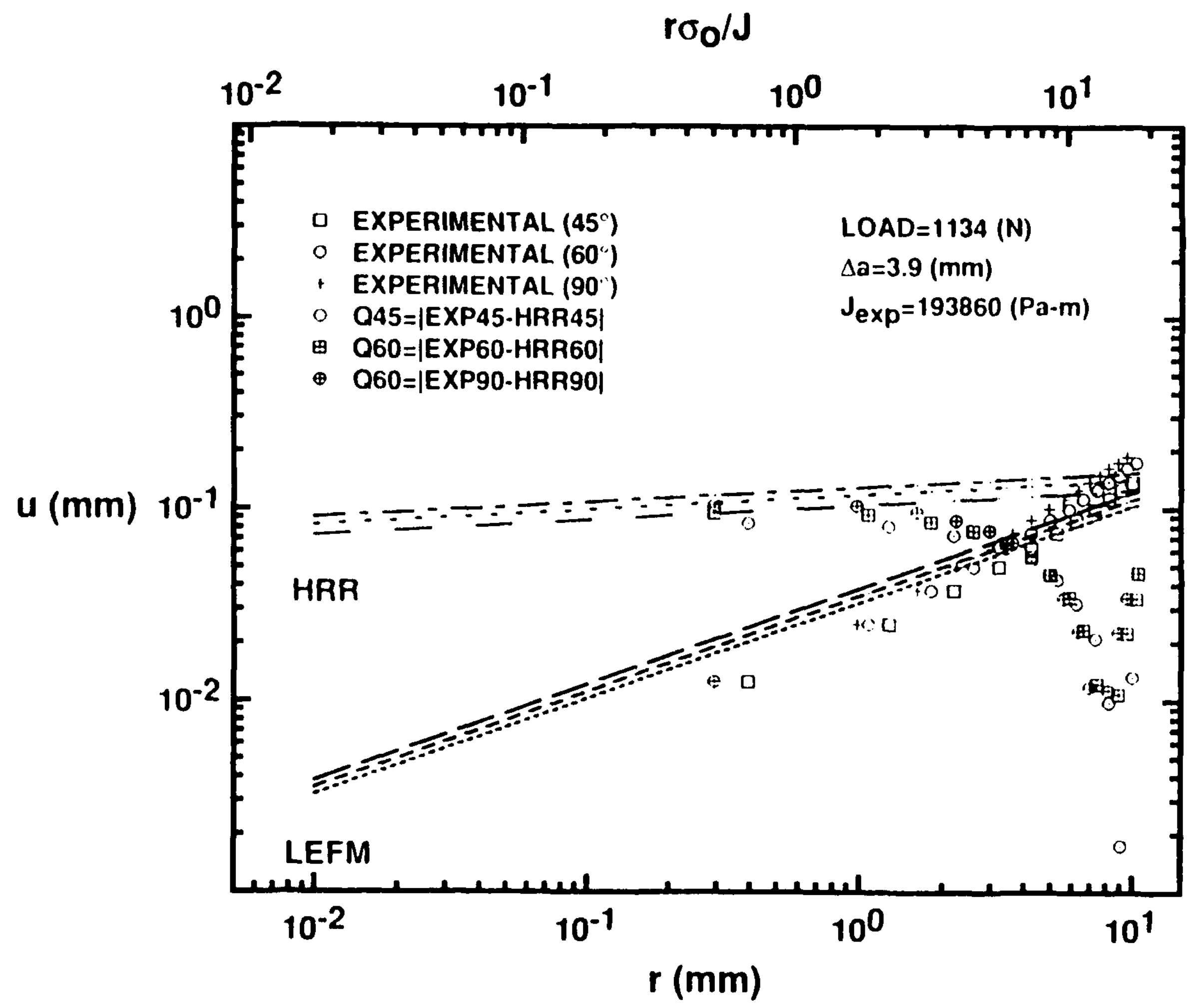


Figure 10a. Crack tip u-displacement in 2024-T3 SEN specimen with large stable crack growth. Coarse grid analysis

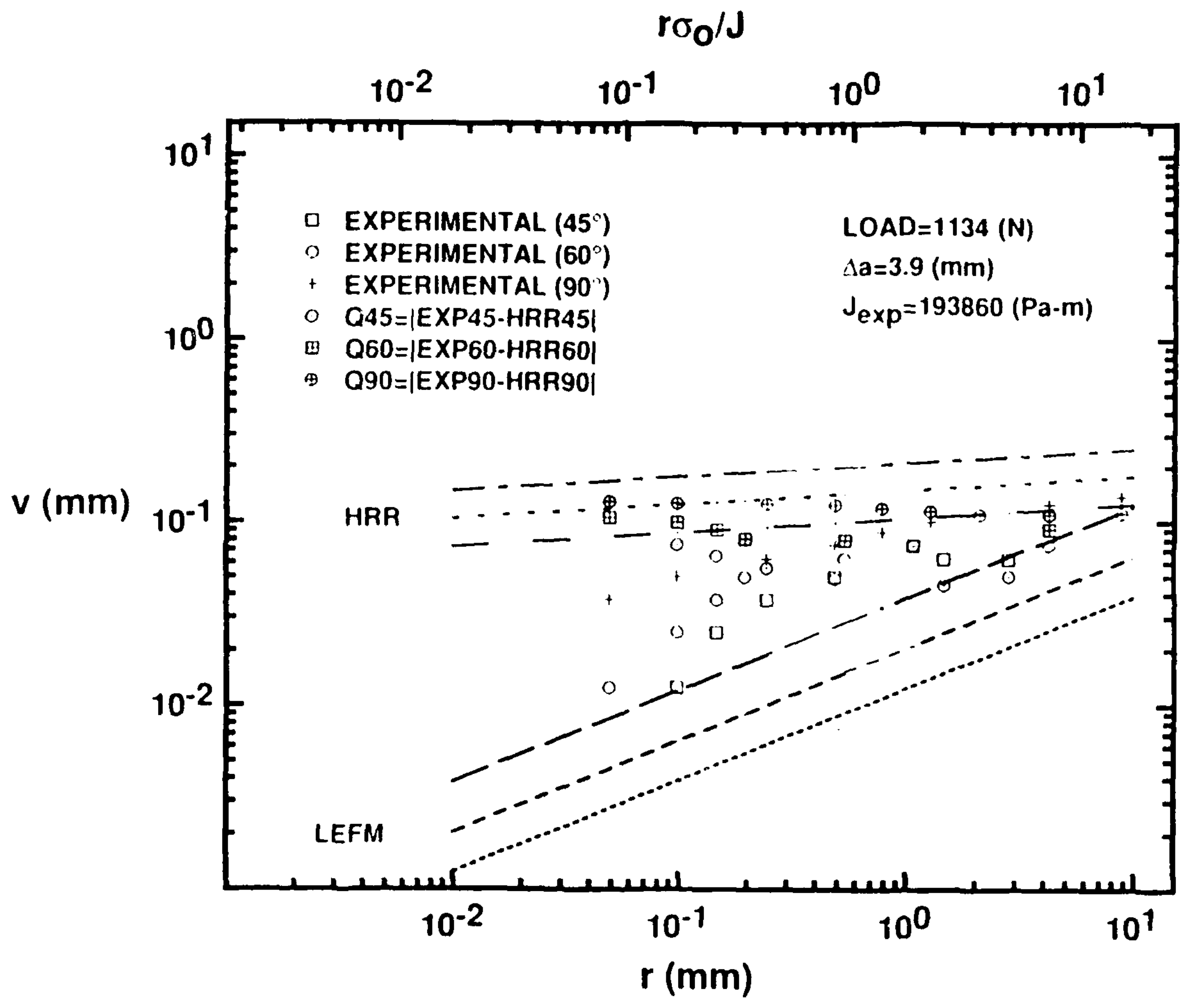


Figure 10b. Crack tip v-displacement in 2024-T3 SEN specimen with large stable crack growth. Coarse grid analysis

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13. ABSTRACT (Maximum 200 words)

Moire interferometry with line densities of 1200 and 40 lines per mm was used to determine the two orthogonal displacements surrounding a stationary and a stably extending crack, respectively in two thin 2024-T3 aluminum alloy, single-edge notched specimens. The displacement fields were used to compute the J-integrals for various contours during crack tip blunting and subsequent crack extension. As expected, the near- and far-field J-integral value prior to stable crack growth coincided with the LEFM strain energy release rate, G, and validated the experimental procedure. The far field J values increased with increasing stable crack growth but the crack tip J values within the nonlinear region remained constant. The HRR displacement field, which was computed from the experimentally determined far field J, agreed with the measured displacement field prior to stable crack growth and progressively deviated from the measured values with stable crack extension.

14. SUBJECT TERMS
Elastic-plastic fracture mechanics, stable crack growth, J-integral, HRR field, J-Q theory, moire interferometry, experimental fracture mechanics.

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